2002

Uniform and variable-rate fertilizer and manure phosphorus for the corn-soybean rotation

David John Wittry
Iowa State University

Uniform and variable-rate fertilizer and manure phosphorus

for the corn-soybean rotation

by

David John Wittry

A dissertation submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Major: Soil Science (Soil Fertility)

Program of Study Committee:
Antonio Mallarino, Major Professor
Alfred Blackmer
Thomas Colvin
Dale Farnham
Randy Killorn

Iowa State University

Ames, Iowa

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Signature was redacted for privacy.

Major Professor

Signature was redacted for privacy.

For the Major Program

To:

Beth, Mike, Matt

and

Mary Wittry

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CHAPTER 1.
GENERAL INTRODUCTION

INTRODUCTION

Over the past decade precision farming (or site-specific agriculture) has evolved from being simply an idea into an accepted management practice for modern agriculture. The challenge that lays before the agricultural research community is to identify how to best utilize these technologies for the benefit of agriculture. This challenge includes not only increasing farm profitability and food production, but also, improving nutrient management, the soil resource in which the crops grow, and water resource conservation.

Variable-rate (VR) technology is a major element of precision farming. This technology allows for varying the application of nutrients or other inputs throughout a field in a cost-effective way. Variable-rate fertilization could improve both farm profitability and nutrient management efficiency compared with traditional, uniform-rate fertilizer application by directing nutrient application to areas with low nutrient content that may otherwise be underfertilized and reducing or eliminating application in areas with nutrient concentrations higher than required for crop production. Water quality also could benefit from a VR application system because excess nutrient application to fields can result in nutrient losses to water resources and diminished water quality. The loss of nutrients from our agricultural areas is directly related to the concentration of the nutrients in that soil. Thus, reducing or eliminating fertilizer application on field areas that already have sufficient nutrient levels for crop production will reduce potential nutrient loss from fields and water quality degradation.

High spatial nutrient variability is documented in the literature and is caused both by natural factors (parent material, topography, climate, native vegetation, etc.) and human management (crop, tillage, fertilization, etc.). The process of growing and harvesting crops removes nutrients from the soil. In order for the soil to remain productive these nutrients need to be replaced. Farmers have long recognized this fact, and have been applying fertilizers and manures to cropland in order to replace the nutrients removed during crop production for many years. Often neither the original fertility level, the removal of nutrients, nor the replacement of these nutrients is uniform over an entire field. The result is nutrient levels that vary considerably across a field. Variable-rate nutrient application has the potential to reduce nutrient variability in soils because it would apply fertilizer to low-testing areas and reduce or eliminate fertilization to high-testing areas. Although VR nutrient application is feasible and it is being used in many regions, a major uncertainty for its use relates to soil sampling methods to best determine nutrient levels and their spatial variability. Questions remain about the effectiveness of currently used soil sampling methods for VR fertilization. In the Corn Belt of the United States, these methods often involve grid soil sampling, in which composite soil samples are collected from a systematic arrangement of cells varying from 1 to 1.8 ha in size. When compared with the traditional soil sampling method based on soil map units and topography, this grid sampling method is more intensive, but also more costly.

The objective of this research was to assess the value of VR P fertilization and P-based liquid swine manure application for corn and soybean production compared with the traditional uniform application method. The value of these two nutrient application methods was assessed by measuring grain yield response and changes of soil-test P values for different parts of several farmers' fields. To achieve this objective, traditional on-farm research methods based on replicated, long and narrow strips were adapted to precision farming technologies. These technologies included grain yield monitors, differential global positioning systems (DGPS), and geographical information systems (GIS).

DISSERTATION ORGANIZATION

This dissertation is presented as two papers suitable for publication in scientific journals of the American Society of Agronomy. The title of the first paper is "Comparison of Uniform and Variable-rate Phosphorus Fertilization for the Corn-Soybean Rotation." The title of the second paper is "Use of Variable-Rate Technology for Agronomic and Environmental Phosphorus-Based Liquid Swine Manure Management." Each paper is divided into sections that include an abstract, introduction with literature review, materials and methods, results and discussion, conclusions, references, and tables. The papers are preceded by a general introduction and are followed by a general summary.

CHAPTER 2.
COMPARISON OF UNIFORM AND VARIABLE-RATE PHOSPHORUS FERTILIZATION FOR THE CORN-SOYBEAN ROTATION

A paper submitted to Agronomy Journal

David Wittry and Antonio Mallarino

ABSTRACT

Variable-rate (VR) technology provides a practical method for changing fertilizer rates within a field. This study compared VR and uniform-rate (UR) P fertilization for corn (*Zea mays* L.)-soybean [*Glycine max* (L.) Merr.] rotations. Grid soil-sampling (0.2-1.7 ha cells), differential global positioning systems (DGPS), and grain yield monitors were used in trials established on six fields (12 site-yr). Replicated treatments were a control and the P requirements of the 2-yr rotation applied once using UR or VR based on soil-test P (STP). Crop characteristics measured, included plant dry weight (DW), plant P concentration (PC), and P uptake (PU) all measured when crops were 15-20 cm tall (V5 growth stage) and harvested grain yield. Phosphorus increased grain yield ($P \leq 0.05$) in five site-yr, all of which had mean STP ≤ 16 mg P kg^{-1} (Bray-P_1 or Mehlich-3). Phosphorus increased DW, PC, and PU in five, six, and seven site-yr, respectively. Crop response to P within most fields tended to be larger in areas testing below Optimum (<16 mg P kg^{-1} STP) and for areas with Clarion soil (fine-loamy, mixed, mesic, Typic

Hapludoll). The method of fertilizer application (VR or UR) did not influence crop responses to P, but the P fertilizer applied with VR was 12-41% less than with UR. Variable-rate P fertilization did not increase yield and observed P fertilizer savings may not offset increased application and soil testing costs. However, VR fertilization may reduce P loss from fields and improve water quality by reducing P fertilization of high-testing field areas.

Abbreviations: ANOVA, analysis of variance; DGPS, differential global positioning systems; DW, dry weight; GIS, geographical information systems; ISU, Iowa State University; PC, P concentration; PU, P uptake; STP, soil-test P; UR, uniform rate; VR, variable rate.

INTRODUCTION

Phosphorus can be a major yield-limiting nutrient for corn and soybean production in many regions. Studies of the spatial variability of STP and other nutrients have revealed large within-field variability in fields with contrasting soil series or long histories of fertilization (Cambardella et al., 1994; Cahn et al., 1994; Mallarino, 1996; Nolin et al., 1996; Gupta et al., 1997; Goedken et al., 1998; Mallarino and Wittry, 2000). McGraw, (1994) reported that in 86% of 392 Minnesota fields sampled using grid-sampling methods, the STP range encompassed at least four of five soil-test interpretation classes. This variability can result from both natural processes and management practices.

In the past, soil fertility evaluation methods or equipment capabilities did not permit practical and economical application of various fertilizer rates within a field. It was difficult to accurately document values for specific locations within a field. Soil-test data that revealed variability in nutrient levels often was averaged, and fields were managed with a uniform rate of fertilizer. Use of DGPS, grain yield monitors, geographical information systems (GIS), and VR technology allows for accurate recording of nutrient levels along with their location and for application of fertilizer at rates that vary across a field (Sawyer, 1994; Wollenhaupt et al., 1994; Schnitkey et al., 1996).

Variable-rate equipment aided by computer controllers can apply crop inputs to specific locations based on the instructions from GIS software packages or computer operators. Variable-rate application has the potential to reduce costs in areas where UR fertilization would overapply fertilizer and to increase yields where fertilizer would be under-applied (Bullock et al., 1994; Cahn et al., 1994; Fixen, 1994; Hammond, 1994; McGraw, 1994; Sawyer, 1994; Franzen and Peck, 1995; Heiniger, 1996; Long et al., 1996; Anderson-Cook et al., 1999; Rehm and Lamb, 2000). Furthermore, several authors have emphasized the potential of VR fertilization to improve water quality because no P fertilizer would be applied to field areas testing above optimum levels for crops (Mulla, 1993; Sawyer, 1994; Franzen and Peck, 1995; Mohamed et al., 1996; Scknitkey et al., 1996; Gupta et al., 1997; Schepers et al., 2000). Most of these studies have focused, however, on describing soil-test variation and assumed crop responses or, when crop response was measured, by using one or more uniform fertilization treatments.

Scarce comparisons of UR and VR fertilization methods for P and K have shown small or no yield differences. Anderson and Bullock (1998) found no differences between UR and VR methods based on a 1-ha grid sampling for P-K mixtures for corn or soybean in six Illinois fields. The result, however, was explained by a lack of crop response to fertilization even though all fields had areas with yield-limiting soil-test values according to local interpretations. Comparisons of UR and VR applications of P-K mixtures for corn, soybean, and wheat (*Triticum aestrivum* L.) in six U.S. Midwest farms (Lowenberg-DeBoer and Aghib, 1999) showed that although VR sometimes resulted in yield increases compared with UR, it seldom increased net returns to fertilization because of increased costs of soil-sampling and application. Although all fields had areas with yield-limiting soil-test values, the mean soil-test values always were above optimum levels for the crops. Research with UR and VR applications of N-P mixtures (Yang et al., 2001) for grain sorghum [*Sorghum bicolor* (L.) Moench] in predominantly low-testing soils showed small yield increases from VR, but concluded increased costs of soil-sampling and application when compared with a uniform application, offset the yield benefit.

Additional research comparing UR and VR P fertilization methods for corn and soybean are needed for fields with variation in STP, soil series, and other production conditions. The objective of this study was to assess responses of corn and soybean grain yield, early plant growth, and early nutrient uptake to UR and VR P fertilization applied with commercial application equipment commonly used in Iowa and the Corn Belt.

MATERIALS AND METHODS

Field P-response strip-trials were conducted in six Iowa farmers' fields that were located in Boone and Guthrie counties. Management practices were those used by each farmer and, thus, corn hybrids, seeding rates, planting dates, and other practices varied among fields. All fields had histories of uniform-rate P fertilization and were managed with a corn-soybean rotation and chisel-plow tillage. Fields with corn residue were chisel-plowed in October or November (fall), and all fields were field-cultivated before planting in April or early May (spring). Areas ranging from 7 to 20 ha were delineated at least 40 m away from field borders to fit experiments based on a replicated strip-trial methodology adapted to precision agriculture technologies (Long et al., 1996; Oyarzabal et al., 1996, Anderson and Bullock, 1998). Treatments were a control and P fertilization using UR or VR application methods. There were four replications in Fields 1-3, five in Field 4, and three in Fields 5-6. Treatments and replications were arranged following a randomized complete-block design. The strip width was 18.3-m in all fields, and strip length was uniform within a field but varied among fields (370 to 800 m). Distance measurements were made with a measuring tape, permanent plastic pipes were buried at each trial corner, and corner coordinates were recorded with a hand-held DGPS receiver.

Composite samples (8-12 cores from a 15-cm depth) were collected before applying the treatments using a systematic, grid-point sampling method (Wollenhaupt et al., 1994). Grid lines were spaced 130 m (1.7-ha cells) in Fields 1-4 and 45 m (0.2-ha cells) in Fields 5 and 6, and cores were collected from 100 m^2 areas at the center of each cell. All soil samples from Fields 1-4 were extracted with the Bray-P_1 solution and samples with pH $\geq$ 7.4 (1:1 dry soil:water ratio) were extracted with the Olsen P solution following procedures described by Frank et al. (1998). Iowa research (Mallarino, 1997) showed high correlation (r = 0.92) between these two P tests, a 0.6 extracted P ratio (Olsen:Bray-P_1) in soils with pH $\leq$7.3, and reduced P extraction with the Bray-P_1 test in many soils with pH > 7.3. Thus, Bray-P_1 values for the few samples with pH > 7.3 (three in Field 1, one in Field 2, one in Field 3) were adjusted accordingly. Samples from Fields 5 and 6 were extracted with the Mehlich-3 P solution (Frank et al., 1998) because field histories suggested that soil pH ranged from very acid (pH near 5.0) to alkaline (up to pH 8.0 due to $CaCO_3$). Extracting with the Mehlich-3 solution and using colorimetric P determination is recommended for all Iowa soils based on local field calibrations (Mallarino, 1997), and interpretations are similar to those for the Bray-P_1 test (Voss et al., 1999).

Table 1 shows descriptive statistics for soil pH, STP, and the distribution of STP values within the five Iowa State University (ISU) interpretation classes. The classes for both the Bray-P_1 and Mehlich-3 P tests are $\leq$8 mg kg^{-1} for Very Low, 9 to 15 mg kg^{-1} for Low, 16 to 20 mg kg^{-1} for Optimum, 21 to 30 mg kg^{-1} for High, and $\geq$31 mg kg^{-1} for Very High (Voss et al., 1999). Table 2 shows summarized information for the two dominant soil series in each field. Experiments in Fields 1 and 2 were established and evaluated only in 1996 (corn in Field 1 and soybean in Field 2) because the fields were sold. The experiment in Field 3 was established in 1997 and evaluated 2 years (corn - soybean). The experiment in Field 4 was established in 1997 and evaluated 4 years (soybean - corn - soybean - corn). Experiments in Fields 5 and 6 were established in 1998 and evaluated 2 years (corn - soybean in Field 5 and soybean - corn in Field 6). Thus, the study included 6 corn crops and six soybean crops. A field-crop code includes a field number (1 to 6), suffixes "a" and "b" to indicate the first and second crop of the rotation and, only for Field 4, suffixes "a_2" and "b_2" indicate crops of a second rotation cycle.

The P fertilizer rates used with both UR and VR methods were the estimated P requirement for the 2-yr corn-soybean rotation applied once before corn or soybean (depending on the field), which is the dominant practice in the Corn Belt. Treatments were reapplied for the second rotation cycle in Field 4 based on new STP from the UR and VR strips. The P rates used (Table 3) followed ISU guidelines based on STP and expected P removal in grain (Voss et al., 1999), except that in Fields 1, 3, and 4 the VR was similar for the Very Low and Low classes. This decision was the result of a consensus reached with the farmers because they thought areas testing Very Low were too small (<16%) and corresponded to isolated cells. The UR treatment was defined on the basis of the median STP value of each experimental area and average expected P removal for each field. The VR treatment was defined on the basis of interpolated STP and the average expected P removal assumed for the UR treatment. The inverse-distance method and a distance-weighting exponent of two (Wollenhaupt et al., 1994) were used to interpolate the STP values. Granulated mono-ammonium phosphate was broadcast on the soil surface before planting with commercial VR spreaders (spinner systems in Fields 1-4 and air-powered systems in Field 5 and 6) equipped with DGPS receivers and controllers, and was incorporated into the soil by field-cultivation. No corrective N rate was used to offset the small amount of N supplied with the mono-ammonium phosphate, but 150 kg N ha^{-1} (the highest N rate suggested by ISU for corn after soybean) was applied across all treatments for corn. Uniform K fertilization was used for each field, and the rate ranged from 110 to 130 kg K ha^{-1} among fields.

Grain yield was harvested and recorded with farm combines equipped with commercial impact flow-rate yield monitors and DGPS receivers. The differential correction was obtained through the U.S. Coast Guard AM signal. The monitors were calibrated by weighing all grain harvested along at least four combine passes over the field lengths. Grain moisture was determined by a sensor located in the combine tank's fill-auger, and yield was corrected to 155 g kg^{-1} H_2O for corn and 130 g kg^{-1} H_2O for soybean. The spatial accuracy was checked by georeferencing border rows and natural markers, such as waterways, with a hand-held DGPS receiver. Yield data were unaffected by borders because the experimental areas were at least 40 m away from any border rows and combine passes that may have included crop rows from neighboring treatment strips were deleted from the data sets. Two 4.57 or 7.62-m wide combine passes were used from each soybean strip, and two to four 4.57-m wide combine passes were used from each corn strip. Yield monitor data were imported to ArcView GIS (Environmental Systems Research Inst. Inc., 380 New York St., Redlands, CA) and were analyzed for common yield monitor errors, such as effects of waterways or grass strips and incorrect settings for grain path time lag through the combine. Affected data were corrected (such as grain path lags) or deleted (such as yield points near waterways or unexpected combine stops).

The aboveground portions of 10 plants were collected from 100 m^2 at the center of areas defined by the width of each treatment strip and the separation distance of the soil sampling grid along the crop rows when plants were 15-20 cm tall. Samples were dried at 65° C, weighed, and ground to pass a 1-mm screen. Total P was analyzed by digesting samples with concentrated H_2SO_4 and H_2O_2 (Digesdahl Analysis System, Hach Inc., CO) and measuring P in the extracts with the Murphy and Riley (1962) colorimetric method. Plant DW and PU are reported on a per-plant basis. Treatment effects on STP were assessed only in Fields 3-6 by collecting composite soil samples (12 cores, 15-cm depth) from the same areas from which plant samples were collected after harvesting the first crop of the rotations.

Treatment effects on grain yield, plant measurements (early DW, PC, and PU), and STP of samples collected after harvest were analyzed with an ANOVA for a randomized complete-block design assuming fixed treatment and block effects (SAS Inst., 2000). The yield data inputs were yield means of all yield monitor points recorded at 1-s intervals within each treatment strip. The treatment sums of squares were partitioned into orthogonal comparisons of the control versus the mean of the two fertilization methods and of differences between the fertilization methods. The ANOVA for the plant measurements and STP after grain harvest were similar to that described for yield, except that data input were those directly derived from each sampling area.

The response of grain yield and plant measurements for field areas with different STP or soil series were assessed by two procedures. A procedure developed by Oyarzabal et al. (1996) and used by others (Mallarino et al., 2001; Bermudez and Mallarino, 2002) was used to evaluate crop response for field areas that tested within the

Iowa STP interpretation classes or that had different soil series. A separate ANOVA in which sources of variation were replications (blocks) and P treatments assessed responses for each STP class or soil series. For the analysis by STP class, yield data were means for areas defined by the width of each treatment strip and the separation distance of the soil sampling grid lines along crop rows. For the analysis by soil series, yield data for each treatment and soil series were determined by overlaying yield maps, experimental layouts, and digitized soil-survey maps (scale 1:12,000). Figure 1 shows an example of the GIS maps. This procedure was not used for STP classes or soil series in which all treatments were not represented in at least two replications. Because of this restriction, small areas with Very Low STP were merged with areas testing Low, small areas testing Very High were merged with areas testing High, and the analysis could not be done for the Optimum class of Field 5. For the same reason, analyses by soil series included the two dominant series (Table 2) in all fields, and a third series only in Fields 3 and 6. The second procedure used regression analyses (SAS Inst., 2000) to study the relationships between yield, DW, PC, or PU response to P with initial STP within-field. The crop and STP data inputs were the same values used for the yield-STP analysis with the first procedure (STP was considered as a continuous variable in this analysis). Relative yield responses however, were used to minimize potential effects of differences in absolute yield or plant DW across and within fields. Relative responses were calculated for each STP value by subtracting data for the control from the mean of the fertilized treatments, dividing the result by the data from the control, and multiplying by 100.

RESULTS AND DISCUSSION

Whole-Field Responses

Phosphorus fertilization increased ($P \leq 0.05$) corn yield in Fields 3a, $4b_2$, and 5a and soybean yield in Fields 5b and 6a (Table 4). The yield of the UR and VR fertilization methods did not differ for either crop in any site-yr. Comparisons of yield responses and initial STP values (Table 1) suggest that the observed yield increases are reasonable because the responsive fields had significant areas testing less than Optimum. A grain yield response to P is likely in soils testing below the Optimum class according to ISU STP interpretations for corn and soybean and previous research based on conventional small-plot methods (Mallarino and Blackmer, 1992; Webb et al., 1992; Mallarino, 1997). The probability of crop response in the Optimum class is small (<20%), and responses are unlikely in the High and Very High classes. The lack of yield differences between UR and VR fertilization suggests that these methods did not differ in low-testing areas or that differences were too small to be detected with a whole-field analysis. The lack of response to VR fertilization observed in this study coincided with results for corn or soybean reported by others (Anderson and Bullock, 1998; Lowenberg-DeBoer and Aghib, 1999).

Phosphorus increased ($P \leq 0.05$) whole-field plant DW in five site-yr (Table 5), PC in six site-yr (Table 6), and PU in seven site-yr (Table 7). Differences between fertilization methods were few and inconsistent across plant measurements and sites. The application method never affected DW. There was a slightly higher corn PC (significant at $P \leq 0.05$) for the UR method compared with the VR method only in Field 5a. Plant PU was more responsive to P than was grain yield, but the application method had no effect. Previous research (Mallarino et al., 1999; Borges and Mallarino, 2000) showed that optimal STP levels for early corn and soybean DW and P uptake are higher than for grain yield. Only Fields 1 and 2, which had the highest mean or median STP of all sites (Table 1), consistently showed no significant ($P \leq 0.05$) P effects on any plant measurement.

Responses in Fields Areas with Different Soil-Test P or Soil Series

Analyses of corn yield response in field areas having different initial STP levels (Table 8) showed significant response to P ($P \leq 0.05$) only for the low-testing areas of Fields 3a, 5a, and 6b, and showed that the application method had no effect. The whole-field results (Table 4) showed corn response to P in Fields 3a, $4b_2$, and 5a but suggested no response in Field 6b. Analyses of soybean yield responses for field areas with different STP (Table 9) showed significant responses to P only for areas testing Optimum or less within Field 6a. The whole-field results showed soybean response to P in Fields 5b and 6a. The VR method increased yield more than the UR method in areas that tested Optimum but not in low-testing areas. This difference cannot be explained satisfactorily because less P was applied with VR than with UR for areas testing Optimum of this field.

Analyses of plant DW, PC, and PU responses for field areas having different initial STP levels showed few statistically supported ($P \leq 0.05$) differential responses to P within a field. Because of this general result, and because of the numerous treatment means involved (three measurements, 12 site-yr, and usually three STP interpretation classes) data are not shown. The plant DW response to P varied across STP classes only in Field 2, where (contrary to expectations) there was an apparently larger soybean DW response in areas testing high but not in areas testing Optimum or Low. Both PC and PU often responded positively to P (which confirmed results of whole-field analyses shown in Tables 5 and 6), but responses usually were observed for all STP interpretation classes within a field. Others (Mallarino et al., 1999; Borges and Mallarino, 2000) have observed significant early DW and PU responses to P in high-testing soils.

Regression analyses of relative grain yield responses with initial STP within each field showed that the response to P decreased linearly from low- to high-testing areas in Fields 5a, 5b, and 6b (correlation coefficients of the relationships are shown in Table 10). These fields contained larger low-testing areas than the others, and the initial soil sampling was done with a smaller grid size (0.2 ha) than for other fields (1.7 ha). No clear conclusions are possible from the study of relationships between response of the plant measurements and STP. There were a few instances in which relationships were significant ($P \leq 0.05$) and negative (as expected), but sometimes were positive (an unexpected result).

Grain yield, DW, PC, and PU often varied among soil series at each field, which was an expected result. However, except for grain yield and PU, responses (or lack of responses) to P and fertilizer application methods were statistically similar ($P \leq 0.05$) for all soil series within a field. Because of this result and the numerous treatment means involved (four crop measurements, 12 site-yr, and two to three soil series in each field), Table 11 shows only grain yield data for the 5 site-yr in which responses differed across soils. The results for these 5 site-yr (four fields) were consistent in showing that the

Clarion soil was more responsive to P than other soils. Differences between application methods for this soil were few, very small, and inconsistent (slightly greater yield for VR in two fields and greater for UR in one field), which suggests random differences. The PU data for these site-yr also showed that the Clarion soil was more responsive than other soils (not shown). In Fields 5 and 6, larger responses for the Clarion soil could be explained by lower initial STP (a difference of 4-6 mg kg^{-1} that changed the interpretation class) compared with other soils and more acidic pH (Table 2). However, the STP and pH were similar (within 2 mg P kg^{-1} and 0.3 pH units) for the soils in Fields 3 and 4. Study of yield levels for each soil series (Table 11), which could have influenced a response to P, indicated no consistent differences. These soil series differ in other properties whose potential impact in responses to P cannot be assessed with the methods used. For example, all soils were formed on loamy glacial till, but the Clarion series occupies higher and steeper positions and is better drained than the other soils. Also, the plow-layer particle size composition often is similar for the Clarion and Nicollet soils (loam) but is coarser than for the Canisteo and Webster soils (silty-clay-loam).

Treatment Effects on Soil-Test P Change after Fertilization

Study of field-average STP changes due to fertilization after crop harvest indicated that P fertilization increased STP ($P \leq 0.05$), and that the application method had an effect only in Field 5 where UR increased STP more than VR. These field averages are not shown or emphasized because STP increases due to fertilization were expected, and because mean STP differences may be misleading because VR applied different amounts of P across a field. Table 12 shows results of STP changes for field areas that initially had STP within different interpretation classes. As expected, P fertilization usually increased STP of areas testing Optimum or less. The application methods had a different effect only for the High class of Field 5, where the UR method increased STP more than the VR method. This result is reasonable because no P was applied with VR in high-testing areas, but some results were difficult to explain. For example, the UR did not increase STP in high-testing areas of several fields even though P was applied, and the VR increased STP in high-testing areas of Fields 5 and 6 where no P was applied. We expected that the VR would increase STP more than the UR in low-testing areas of Fields 1 to 4 because more P was applied with the VR. We did not expect such a difference in Fields 5 and 6 because both methods applied the same rate in areas testing Very Low, and the VR method applied less fertilizer than the UR in areas testing Low. Also, we expected the UR would increase STP more than the VR in high-testing areas because the UR applied P and the VR did not.

Interpretive Summary Discussion

Procedures based on ANOVA or regression did not confirm expected larger crop responses to P applied with VR in low-testing areas compared with UR. This result could be explained by several reasons. One possibility is that fertilization rates applied to low-testing areas with both application methods were sufficient to produce maximum crop yield. The P fertilizer recommendations used in Iowa and the Corn Belt for low-testing soils often include a build-up component or it is recognized that the recommended rates will result in STP build-up (Voss et al., 1999). Results of soil sampling in our study (although highly variable) showed increased STP values for low-testing areas. Sufficient P to maximize yield is even more likely for the first crop of the rotation when the 2-yr recommendation is applied once. Mallarino and Blackmer (1992) showed that corn yield responses in short-term (one crop) experiments conducted in several low-testing Iowa soils were similar for P rates ranging from 25 to 75 kg P ha^{-1}. These observations demonstrate that the choice of rates used at research or production agriculture levels may not have a large impact on crop responses. The criteria used for selecting rates in this study are commonly used in production agriculture, and the lack of yield differences between fertilization methods coincides with results of other research, which also was based on current fertilizer recommendation systems (Anderson and Bullock, 1998; Lowenberg-DeBoer and Aghib, 1999). Insufficient precision of the VR technology, including controllers response or uniformity of application across the spreading width, could also partly explain the results of this study (and of other studies as well). The methods used in this study however, are those most frequently used for VR application across the Corn Belt.

Lack of yield difference between UR and VR, poor relationships between STP and grain yield (which was harvested with yield monitors) or plant measurements (which were sampled by hand) when using either ANOVA or regression procedures, and some unexpected results for STP change also could be explained by very high small-scale STP variability and (or) inadequacy of the soil sampling methods used. Large STP variability and poor relationships between crop response and initial STP even in Fields 5 and 6, where a 0.2-ha grid sampling scheme with 12 cores per sample was used, points to the problem of high small-scale STP variation. Previous research based on denser sampling methods showed very high small-scale variability in STP or plant DW, PC, and PU in Iowa fields (Cambardella et al., 1994; Mallarino, 1996; Borges and Mallarino, 1997, 1998; Mallarino and Wittry, 2000). Although the grid-point sampling method used in this study is the most frequently used in Iowa and the Corn Belt, the results suggest that this method may need to be reexamined. For example, Schepers et al. (2000) showed that using point samples from different parts of a grid cell often results in very different soil-test values, and suggested that grid-point sampling based on grid distances even smaller than those that can be afforded by farmers may not provide reliable information.

Although VR fertilization did not increase yield compared with UR fertilization, there were large differences in amounts of fertilizer applied. Calculations from data in Table 3 show that use of VR resulted in less P applied than use of UR in all fields (23, 19, 12, 19, 41, 31% less P in Fields 1-6, respectively). Thus, use of VR could result in fertilizer savings. However, these differences cannot be directly extrapolated to other fields because differences in P applied are highly affected by STP levels, within-field STP variation, and the fertilizer rates chosen. Also, this advantage for VR could be partially or completely offset by increased application costs and likely increased soil sampling costs if the sampling is based on grid sampling as others have shown (Anderson and Bullock, 1998; Lowenberg-DeBoer and Aghib, 1999; Yang et al., 2001). Information received from farmers and custom fertilizer applicators indicates that VR fertilization usually is based on grid soil sampling using a 1-ha grid size, and that application charges are based on the entire field area even though fertilizer may not be applied to high-testing areas. Reduced P fertilizer application with VR, however, can reduced P loss from fields and improve water quality because less P fertilizer is applied to field areas testing above optimum levels for crops.

CONCLUSIONS

Phosphorus fertilization often increased crop grain yield, DW, and PU when STP was less than Optimum (<16 mg P kg^{-1}). The Clarion soil series was more responsive to P than other soils in four fields, a difference that likely resulted from lower STP and pH in two fields but that could not be explained for the other fields. The method of fertilizer application did not influence the crop response to P fertilization. The results suggested that use of existing soil-test interpretations and P recommendations combined with very high small-scale STP variation may explain the lack of yield difference between fertilization methods. Although VR did not increase yield compared with UR, its use resulted in 12-41% less P applied compared with UR. A lack of yield difference between fertilizer application methods combined with larger application costs and likely larger soil testing costs for VR may offset the economic benefit of reduced P application. Reduced P application to high-testing areas with VR, however, likely reduces the risk of P loss from fields and may result in more environmentally sound P management.

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Table 1. Descriptive statistics for soil-test P and pH, and soil-test P distribution within Iowa State University interpretation classes for six fields.

Field	Descriptive statistics† for soil-test P				
	Mean	Median	Min	Max	SD
	mg kg^{-1}				
1	18	16	8	34	8
2	24	18	13	97	18
3	15	14	6	34	8
4	16	16	8	24	5
5	12	8	4	40	9
6	11	8	5	29	6

Field	Descriptive statistics for soil pH				
	Mean	Median	Min	Max	SD
1	6.7	6.5	5.8	7.8	0.7
2	6.3	6.1	5.8	8.0	0.6
3	6.2	6.1	5.7	7.5	0.5
4	5.9	6.0	5.7	6.2	0.1
5	6.7	6.4	5.4	7.9	0.9
6	5.9	5.5	5.1	7.5	0.7

Field	Field area for five soil-test P classes ‡				
	VL	L	Opt	H	VH
	%				
1	9	41	17	17	16
2	0	25	50	17	8
3	16	42	17	17	8
4	12	28	32	28	0
5	17	50	4	13	16
6	8	67	13	12	0

† Min = minimum, Max = maximum, SD = standard deviation.
‡ VL = very low, L = low, Opt = optimum, H = high, and VH = very high.

Table 2. Predominant soil series in the experimental areas and average soil-test P and pH (0-15 cm depth) of six fields.

	Dominant soil series					Second dominant soil series				
Field	Series	Classification †	Area	STP ‡	pH	Series	Classification	Area	STP	pH
			%	$mg\ kg^{-1}$				%	$mg\ kg^{-1}$	
1	Webster	T. Endoaquoll	56	22	6.8	Nicollet	A. Hapludoll	38	11	6.2
2	Nicollet	A. Hapludoll	57	19	6.0	Webster	T. Endoaquoll	27	31	5.9
3	Webster	T. Endoaquoll	44	16	6.1	Clarion	T. Hapludoll	36	16	5.9
4	Clarion	T. Hapludoll	77	16	5.7	Webster	T. Endoaquoll	18	14	6.0
5	Webster	T. Endoaquoll	36	19	7.0	Clarion	T. Hapludoll	33	13	5.7
6	Clarion	T. Hapludoll	44	12	5.6	Canisteo	T. Endoaquoll	26	16	6.8

† A. = Aquic and T. = Typic.

‡ Mean soil-test P calculated from initial samples collected by grid soil sampling.

Table 3. Target P application rates, uniform-rate and variable-rate for six fields.

Field	Uniform-rate	Variable-rate for various STP classes †			
		Very low	Low	Optimum	AVG ‡
	kg P ha^{-1}				
1	45	55	55	45	35
2	45	na §	55	45	36
3	45	55	55	45	40
4	45	55	55	45	36
5	70	70	55	35	41
6	70	70	55	35	48

† Variable P rates for the Bray-P_1 interpretation classes Very Low (<8 mg kg^{-1}), Low (9-15 mg kg^{-1}), and Optimum (16-20 mg kg^{-1}).

‡ AVG = weighted average variable P rate for the entire experimental areas, including not fertilized high-testing areas.

§ na = not applicable (there were no field areas testing Very Low).

Table 4. Corn and soybean grain yield response to P applied with two fertilization methods.

Crop	Field †	Year	Treatment and grain yield: Check	Variable	Uniform	P effect ‡
			---------- Mg ha^{-1} ----------			$P > F$
Corn	1a	1996	11.21	11.19	11.09	0.58
	3a	1997	9.13	9.38	9.24	0.05
	4b	1998	10.34	9.96	10.22	0.11
	4b$_2$	2000	8.34	8.41	8.50	0.03
	5a	1998	10.04	11.06	11.02	0.01
	6b	1999	9.53	9.67	9.72	0.17
Soybean	2a	1996	4.02	4.08	4.12	0.21
	3b	1998	3.32	3.42	3.44	0.12
	4a	1997	2.74	2.76	2.80	0.31
	4a$_2$	1999	3.33	3.38	3.35	0.20
	5b	1999	2.59	2.75	2.92	0.05
	6a	1998	3.27	3.72	3.72	0.02

† Suffixes "a" and "b" in the field code identify the first and second crop of the rotation cycle (the P for the 2-yr rotation was always applied once before the first crop). Second crops in Fields 1 and 2 could not be evaluated. Suffixes "a$_2$" and "b$_2$" for Field 4 indicate that treatments were reapplied for a second rotation cycle.

‡ Mean P effect = probability of the P main effect. Comparisons between fertilization methods (UR vs. VR) were not significant ($P \leq 0.05$).

Table 5. Corn and soybean early dry weight (DW) response to P applied with two fertilization methods.

Crop	Field	Year	Treatment and plant DW			P effect †
			Check	Variable	Uniform	
			---------- g plant^{-1} ----------			$P > F$
Corn	1a	1996	0.91	0.96	1.04	0.11
	3a	1997	1.68	1.87	1.89	0.03
	4b	1998	1.09	1.15	1.10	0.25
	$4b_2$	2000	1.43	1.65	1.73	0.04
	5a	1998	1.09	1.34	1.43	0.02
	6b	1999	3.85	4.07	4.16	0.15
Soybean	2a	1996	1.79	1.81	1.81	0.75
	3b	1998	1.10	1.13	1.14	0.54
	4a	1997	1.98	2.39	2.51	0.01
	$4a_2$	1999	1.68	1.64	1.71	0.99
	5b	1999	2.03	1.98	2.11	0.94
	6a	1998	1.80	2.09	2.14	0.02

† Mean P effect = probability of the P main effect. Comparisons between fertilization methods (UR vs. VR) were not significant ($P \leq 0.05$).

Table 6. Response of corn and soybean early plant P concentration (PC) to P applied with two fertilization methods.

Crop	Field	Year	Treatment and plant PC			
			Check	Variable	Uniform	P effect †
			---------- g kg^{-1} ---------			$P > F$
Corn	1a	1996	2.97	3.08	3.09	0.30
	3a	1997	4.24	4.24	4.32	0.59
	4b	1998	2.88	3.04	3.12	0.19
	$4b_2$	2000	3.03	3.40	3.42	0.01
	5a	1998	2.04	2.43	2.92	0.01 ‡
	6b	1999	2.98	3.19	3.29	0.07
Soybean	2a	1996	3.15	3.24	3.22	0.12
	3b	1998	3.11	3.03	3.26	0.75
	4a	1997	3.44	3.61	3.57	0.01
	$4a_2$	1999	3.53	3.80	3.87	0.01
	5b	1999	2.25	2.55	2.45	0.01
	6a	1998	2.90	3.03	3.13	0.05

† Mean P effect = probability of the P main effect.

‡ Significant difference ($P \leq 0.05$) between fertilization methods (UR vs. VR).

Table 7. Response of corn and soybean early plant P uptake to P applied with two fertilization methods.

Crop	Field ‡	Year	Treatment and plant P uptake			P effect †
			Check	Variable	Uniform	
			---------- mg P plant^{-1} ---------			$P > F$
Corn	1a	1996	2.82	3.12	3.25	0.21
	3a	1997	7.11	7.97	8.17	0.04
	4b	1998	3.18	3.52	3.45	0.14
	$4b_2$	2000	4.38	5.66	5.96	0.01
	5a	1998	2.22	3.38	4.28	0.01
	6b	1999	11.53	13.05	13.70	0.05
Soybean	2a	1996	5.68	5.88	5.86	0.38
	3b	1998	3.49	3.49	3.73	0.58
	4a	1997	6.84	8.62	8.96	0.01
	$4a_2$	1999	5.93	6.20	6.66	0.03
	5b	1999	4.64	5.15	5.28	0.27
	6a	1998	5.20	6.34	6.68	0.01

† Mean P effect = probability of the P main effect. Comparisons between fertilization methods (UR vs. VR) were not significant ($P \leq 0.05$).

Table 8. Corn grain yield response to P for field areas testing within different soil-test P interpretation classes.

Field	Year	STP class †	Treatment and grain yield			P effect ‡
			Check	Variable	Uniform	
			----------	kg ha^{-1}	----------	$P > F$
1a	1996	VL-L	11.34	11.28	11.12	0.33
		Opt	10.99	10.91	10.79	0.45
		H	11.13	11.21	11.19	0.88
3a	1997	VL-L	9.09	9.39	9.23	0.03
		Opt	9.45	9.39	9.42	0.60
		H	9.02	9.33	9.16	0.06
4b	1998	VL-L	10.27	9.82	10.08	0.10
		Opt	10.11	9.88	10.17	0.64
		H	10.72	10.26	10.48	0.30
$4b_2$	2000	VL-L	8.20	8.29	8.38	0.13
		Opt	8.72	8.73	8.88	0.71
		H	8.09	8.20	8.18	0.26
5a	1998	VL-L	9.89	11.07	10.91	0.01
		H	10.48	11.06	11.36	0.07
6b	1999	VL-L	9.35	9.58	9.66	0.05
		Opt	9.65	9.93	9.48	0.55
		H	10.43	9.95	10.33	0.55

† STP class = soil-test P classes. VL = very low, L = low, Opt = optimum, and H = high. No P was applied to areas testing high with the variable-rate method.
‡ P effect = probability of the P main effect. Comparisons between fertilization methods (UR vs. VR) were not significant ($P \leq 0.05$).

Table 9. Soybean grain yield response to P for field areas testing within different soil-test P interpretation classes.

Field	Year	STP class †	Check	Variable	Uniform	P effect ‡
			Treatment			
			---------- kg ha^{-1} ----------			$P > F$
2a	1996	L	4.06	4.06	4.14	0.50
		Opt	3.98	4.07	4.10	0.20
		H	4.05	4.13	4.16	0.22
3b	1998	VL-L	3.37	3.43	3.46	0.37
		Opt	3.33	3.49	3.51	0.18
		H	3.18	3.34	3.34	0.31
4a	1997	VL-L	2.82	2.79	2.86	0.90
		Opt	2.63	2.70	2.66	0.28
		H	2.77	2.76	2.89	0.11
$4a_2$	1999	Vl-L	3.33	3.33	3.33	0.38
		Opt	3.36	3.44	3.41	0.18
		H	3.28	3.40	3.31	0.21
5b	1999	VL-L	2.69	2.91	3.05	0.12
		H	2.30	2.33	2.59	0.29
6a	1998	VL-L	3.23	3.67	3.73	0.01
		Opt	3.40	4.19	3.75	0.02 §
		H	3.43	3.57	3.60	0.09

† STP class = soil-test P classes. VL = very low, L = low, Opt = optimum and H = high. No P was applied to areas testing high with the variable-rate method.
‡ P effect = probability of the P main effect.
§ Additional significant difference ($P \leq 0.05$) between fertilization methods (UR vs. VR).

Table 10. Correlation coefficients of relationships between initial STP and relative response to P (average for two application methods) for grain yield, early plant dry weight (DW), P concentration (PC), and P uptake (PU).

Crop	Field	Year	Yield	DW	PC	PU
			--------- Correlation coefficients --------			
Corn	1a	1996	0.19	-0.10	0.01	-0.08
	3a	1997	0.05	0.50*	-0.04	0.44*
	4b	1998	0.02	-0.12	-0.18	-0.19
	$4b_2$	2000	-0.03	0.03	-0.16	-0.04
	5a	1998	-0.57*	-0.65*	-0.49*	-0.59*
	6b	1999	-0.49*	-0.34	-0.15	-0.35
Soybean	2a	1996	0.22	0.75*	0.35	0.82*
	3b	1998	0.39	-0.04	-0.12	-0.09
	4a	1997	0.14	0.01	-0.20	-0.05
	$4a_2$	1999	0.18	0.06	-0.09	0.02
	5b	1999	-0.34	-0.26	-0.45*	-0.37
	6a	1998	-0.32	-0.12	-0.29	-0.20

* Significant at $P \leq 0.05$.

Table 11. Grain yield response to P for field areas with different soil series for fields and crops for which responses among soils differed.

Crop	Field	Soil series	Treatment and grain yield: Check	Variable	Uniform	P effect †
			---------- Mg ha^{-1} ----------			$P > F$
Corn	3a	Clarion	8.73	9.17	8.96	0.01 ‡
		Nicollet	9.20	9.53	9.26	0.27
		Webster	9.38	9.49	9.40	0.45
	$4b_2$	Clarion	8.33	8.34	8.50	0.03 ‡
		Webster	8.37	8.44	8.28	0.97
Soybean	4a	Clarion	2.66	2.73	2.76	0.01
		Webster	3.13	2.75	2.95	0.14
	5b	Clarion	3.06	3.49	3.69	0.01
		Webster	2.50	2.51	2.72	0.38
	6a	Canisteo	2.89	3.22	3.03	0.25
		Clarion	3.09	3.74	3.55	0.01 ‡
		Nicollet	3.70	3.79	4.25	0.44

† P effect = probability of the P main effect.

‡ Additional significant difference ($P \leq 0.05$) between fertilization methods (UR vs. VR).

Table 12. Effect of three P fertilization treatments on soil-test P change for various interpretation classes. †

Field	STP class ‡	Treatment and soil-test P			P effect §
		Check	Variable	Uniform	
		--------- mg kg^{-1} ---------			$P > F$
3	VL-L	5.7	7.7	10.4	0.26
	Opt	-1.3	2.8	0.3	0.31
	H	-2.8	-5.5	-1.5	0.78
4	VL-L	9.3	16.2	14.3	0.09
	Opt	-0.3	6.3	9.5	0.02
	H	-6.3	-2.9	0.7	0.06
4 ¶	VL-L	5.5	16.8	16.9	0.01
	Opt	4.8	19.8	19.9	0.01
	H	-3.2	-7.2	-5.6	0.27
5	VL-L	-0.3	14.9	20.4	0.01
	H	6.4	14.6	23.1	0.06 #
6	VL-L	1.6	11.8	17.1	0.01
	Opt	-1.3	17.0	12.7	0.02
	H	-3.0	11.3	12.7	0.01

† Difference for each treatment between soil-test P measured before treatment application and 7 months later (after one crop harvest).

‡ STP class = soil-test P classes. VL = very low, L = low, Opt = optimum and H = high. No P was applied to areas testing high with the variable-rate method.

§ P effect = probability of the P main effect.

¶ Data for the second rotation cycle in Field 4.

Additional significant difference ($P \leq 0.05$) between fertilization methods (UR vs. VR).

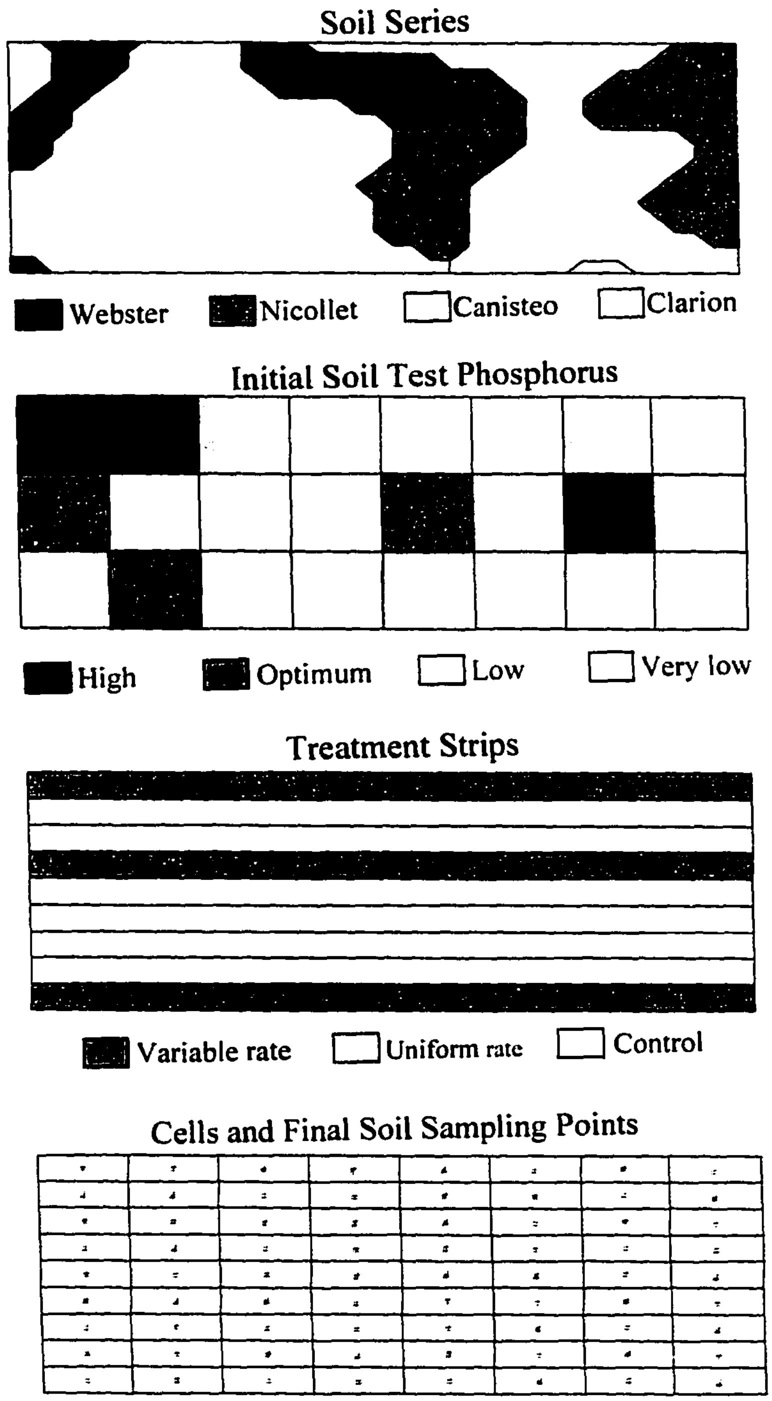

Fig. 1. Example of soil series map, initial soil sampling grids, treatments strips that correspond to areas for which strip yield means were calculated, and final soil-sampling cells that correspond to areas for which cell-treatment means were calculated.

CHAPTER 3.
USE OF VARIABLE-RATE TECHNOLOGY FOR AGRONOMIC AND ENVIRONMENTAL PHOSPHORUS-BASED LIQUID SWINE MANURE MANAGEMENT

A paper to be submitted to Agronomy Journal

David J. Wittry and Antonio P. Mallarino

ABSTRACT

Land application is the most common method for utilizing manure produced by the livestock industry. Manure applications at rates that exceed crop P removal are increasing soil-test P (STP) in many regions. Precision agricultural technologies and variable-rate (VR) application can improve nutrient management and provide an environmentally responsible method to distribute manure. This study used a strip-trial methodology and precision agriculture methods to compare uniform-rate (UR) and VR manure application based on STP for soybean [*Glycine max* (L.) Merr.] - corn (*Zea mays* L.) rotations in two fields and two rotation cycles. Liquid swine manure was applied before planting soybean to supply the P requirement of the 2-year rotation, and uniform fertilizer N was applied to corn. Manure increased whole-field crop yield ($P \leq 0.05$) in five site-years but the application methods had no effect. Analyses for field areas with contrasting STP showed frequent yield response to manure in low-testing areas and

seldom in optimum or high-testing areas. Larger yield response to VR than to UR in low-testing field areas in one site-year did not influence the whole-field yield response significantly. On average, the VR method applied 11% more manure compared with UR. Use of VR reduced STP variability by increasing STP more than UR in low-testing areas and reducing or not affecting STP in high-testing areas. Use of VR may not result in increased economic benefits for producers, but allows for better management of liquid manure and reduces the risk of P loss to water resources from manured fields.

Abbreviations: ANOVA, analysis of variance; DGPS, differential global positioning systems; ISU, Iowa State University; RCBD, randomized complete block design; STP, soil-test P; UR, uniform rate; VR, variable rate.

INTRODUCTION

Livestock production is a vital component of the economy in the United States. Livestock and their products provided over $95 million in cash receipts to farmers in 1999 (Agricultural Statistics Board, 2001). In Iowa there were 3.7 million cattle and 15.4 million hogs in 2000 (Agricultural Statistics Board, 2001). Manure generated by this industry provides nutrients that can be effectively utilized by crops when it is handled appropriately (McIntosh and Varney, 1972; Sutton et al., 1982; Jokela, 1992; Schlegel, 1992; Eghball and Power, 1999; Adeli and Varco, 2001). Eghball and Power (1994) calculated that the N, P, and K contained in cattle feedlot manure would have an annual value of $461 million if purchased as fertilizer. Crop-land application is the most common and currently the only viable method for utilizing manure (Eghball and Power, 1994; Lorimor and Lawrence, 2001). Concentration of large livestock feeding operations along with the high cost of transporting a diluted material plus N-based manure applications that exceed crop P needs often lead to a build-up of STP (Sutton et al., 1982; Kingery et al., 1993; Muir, 2001). Studies have shown that P concentration in runoff increases with increasing STP (Sharpley, 1995; Pote et al., 1996; Pote et al., 1999; Klatt et al., 2001). Surface runoff containing excess P that is delivered to water bodies can cause eutrophication (Sharpley et al., 1996). Klatt et al. (2001) concluded that a reduction of unneeded P application to high-testing field areas would reduce P loss from agricultural areas of an Iowa watershed.

Variable-rate application of manure would help reduce environmental consequences by applying manure only where nutrients are needed. Several authors have emphasized the potential of VR fertilization to improve water quality by reducing fertilization where nutrients are above levels required for optimum crop production (Sawyer, 1994; Franzen and Peck, 1995; Mohamed et al., 1996; Scknitkey et al., 1996; Gupta et al., 1997). Furthermore, Morris et al. (1999) demonstrated that manure application equipment can be easily modified to apply VR manure. Our objectives were to evaluate corn and soybean response to UR and VR liquid swine manure applied before planting soybean and to study the effect of the two application methods on STP.

MATERIALS AND METHODS

Field strip-trials were conducted during 4 years on two Iowa farmer's fields managed with a corn-soybean rotation. An area of approximately 15 ha of each field was selected for the experiments. Both fields had previous histories of uniform P fertilization and corn-soybean rotations. Tillage consisted of chisel-plowing the corn residue in the fall and field-cultivating before both crops in the spring. A complex map unit of Clyde (Typic Endoaquoll) and Floyd (Aquic Hapludoll) soils predominated in both sites (45 to 46% of the areas). Second dominant soils were Kenyon (Typic Hapludoll) in Site 1 (13% of the area) and Readlyn (Aquic Hapudoll) in Site 2 (29% of the area). Initial composite soil-samples (12 cores from a 15-cm depth) were collected using a grid-point sampling method (Wollenhaupt et al., 1994). Grid lines were spaced 55 m in both directions and cores were collected from approximately 100 m^2 near the center of each cell. Soil samples were analyzed for P, pH, K, and organic matter by procedures recommended for the North-Central region (Brown, 1998). Iowa State University (ISU) STP interpretation classes for the Bray-P_1 test is used throughout this paper. The five classes are as follows: $\leq$8 mg kg^{-1} for Very Low, 9 to 15 mg kg^{-1} for Low, 16 to 20 mg kg^{-1} for Optimum, 21 to 30 mg kg^{-1} for High, and $\geq$31 mg kg^{-1} for Very High (Voss et al., 1999).

The treatments were a control with no manure application, a UR of manure, and a VR of manure, which were applied before planting soybean to strips 18.3-m wide and 605-660 m long. Randomized complete-block designs (RCBD) were used in both fields. There were five replications in Field 1 and four in Field 2. Liquid swine manure from the same underground storage pit was used, and its average nutrient content was 6.0 g L^{-1} N, 1.8 g L^{-1} P, and 2.0 g L^{-1} K. A Uniform rate of at least 150 kg N ha^{-1} (anhydrous ammonia) was applied across all treatments for the corn crops. The manure was broadcast with a slurry tank spreader equipped with a differential global positioning receiver (DGPS), a flow meter, and a controller, and was incorporated by chisel-plowing and/or field-cultivation. The corn crops were evaluated without additional P fertilizer or manure. The experiment at Site 1 was established in 1997 and treatments were applied in the spring of 1997 and 1999. The experiment at Site 2 was established in 1998 and treatments were applied in the spring of 1998 and 2000. The suffixes "a", "b", "c", or "d" sometimes were added to the site numeric code to denote the first through fourth year of the experiments.

The manure rates used are shown in Table 1. The UR of manure was calculated to supply 51 kg ha^{-1} of total P after reaching a consensus with the cooperating farmers for using their normal manure rate for the 2-yr rotation. This rate is within the high range of P maintenance rates recommended by ISU (based on expected P removal in grain) for this 2-year rotation (Voss et al., 1999). The VRs of manure were based on STP values from the initial soil sampling and were calculated to supply the P requirements of the 2-year rotation. The target VR rates were 85 kg P ha^{-1} for areas testing Very Low, 68 kg P ha^{-1} for areas testing Low, and 42 kg P ha^{-1} for areas testing Optimum. A mistake in the computer programming resulted in a rate of 34 kg P ha^{-1} being applied to high-testing areas of Site 1 in the first year.

Grain yield was harvested and recorded with farm combines equipped with impact flow-rate yield monitors and DGPS receivers. The yield monitors recorded data at 1-s intervals, and differential correction was obtained through the U.S.A. Coast Guard AM signal. Grain moisture was determined by a sensor located in the combine auger, and yield was corrected to 155 g kg^{-1} H_2O for corn and 130 g kg^{-1} H_2O for soybean. The yield data for the second year in Site 1 (corn) was lost due to a yield monitor problem. Thus, seven site-years of data were available.

Field-average grain yields were analyzed using an analysis of variance (ANOVA) for a RCBD for which data input were means for each treatment strip. The treatment sums of squares were partitioned into comparisons of a mean P effect and a comparison of the two application methods. A second procedure analyzed treatment effects on yield separately for field areas with different STP interpretation classes. This procedure was developed by Oyarzabal et al. (1996) and later used by Mallarino et al. (2001b). Yield data for this procedure were means for areas defined by the soil sampling grid lines along crop rows and the width of each treatment strip across crop rows. The STP input were the initial values for each sampling cell. Three yield treatment means corresponded to each STP value. To assess the consistency of treatment effects for field areas with different STP classes, a one-way ANOVA was used for each STP class and site-year.

Simple correlation analysis was used to study relationships between STP and yield response to manure. The STP data input were values from the soil sampling grid-cells at each site. The yield data input were data triplets (for control, UR, and VR treatments) from the cells used for the previously described analyses. Relative responses were used to minimize effects caused by variation in yield potential across and within sites. Relative responses were calculated by subtracting the yield of the control treatment from the mean of the manured treatments (UR and VR), dividing the result by the control, and multiplying by 100.

Composite soil-samples (12 cores from a 15-cm depth) were collected after harvesting each crop for STP analyses from 100-m^2 areas near the center of cells defined by the initial soil sampling grid lines along crop rows and the width of each treatment strip across crop rows. Changes in STP due to manure and cropping were calculated by subtracting the initial STP from the mean STP value of samples collected after harvesting the soybean and corn crops of each rotation cycle. The initial STP data from samples taken from the center of the larger initial cells was assumed to represent STP of the whole cell. Potential treatment effects on STP change were assessed by using an ANOVA similar to that used for assessing crop responses to the P treatments for field areas with different STP interpretation classes. The standard deviation of the final soil samples for each treatment was used to assess the effect of the manure application methods on STP variability.

RESULTS AND DISCUSSION

Analyses of soil samples collected before treatment application showed that STP in both sites spanned four to five STP interpretation classes. Areas testing Very Low or Low were 70% in Site 1 and 68% in Site 2 (Table 1). Mean and median STP values were 12 and 13 mg kg^{-1} for Site 1 and 15 and 11 mg kg^{-1} for Site 2. Large and frequent yield responses to P should be expected in low-testing field areas according to ISU fertilizer recommendations for corn and soybean (Voss et al., 1999). Both sites also contained significant high-testing areas that require no P according to current recommendations.

Whole-field analyses of yield (Table 2) showed that manure application increased ($P \leq 0.05$) soybean yield in Sites 1c and 2c and corn yield in all sites (Sites 1d, 2b, and 2d). Although the methods used cannot dismiss possible effects of nutrients in the manure other than P, the responses likely were due to the manure P because almost 70% of the field areas tested below the Optimum STP class. Also, a uniform rate of at least 150 kg N ha^{-1} was applied across all treatments for the corn crops, and both mean and median soil-test K values were in the Optimum K class. Results of late-season cornstalk NO_3^- tests (not shown) indicated no difference in N concentration due to the treatments, which suggests the uniform N fertilization eliminated any possible residual N effect from manure applied to the previous soybean crop. There were no yield differences between the VR and UR methods of manure application for any crop.

Analyses of soybean yield response for field areas having different initial STP levels (Table 3) showed statistically significant ($P \leq 0.05$) response to manure in the Low and Very Low classes in every site-year with only one exception. The exception was for the Very Low class in Site 1a, and this result cannot be explained satisfactorily. The manure application method had no effect on yield response. There was no response to manure in areas with STP Optimum, High, or Very High. Similar analyses for corn (Table 4) showed significant responses to manure in the low-testing classes of all site-years, in the Optimum class of one site-year (Site 2d), and no response in the high-testing classes. The manure application methods differed only in one site-year (Site 1d), where the VR method produced higher corn yield than the UR method in field areas testing Very Low.

Regression analyses of yield response on initial STP also showed a higher response to manure in soils with low STP. Except for Site 1a, relationships showed decreasing response with increasing STP (linear correlation coefficients ranged from -0.42 to -0.59) and were highly significant ($P \leq 0.01$). Results of ANOVA and regression analyses demonstrate that manure can supply P needed by both corn and soybean, and add support to the assumption that corn responses in low-testing areas were due to the manure P and not the manure N.

The results demonstrate that manure P can be withheld from high-testing field areas without causing a yield reduction. However, results also suggest that use of VR liquid manure applications will seldom increase yield above those from a UR. The possibility of yield increases has been proposed as a potential benefit for VR systems but it has not been well documented. Research with P fertilizers (Mallarino and Wittry, 1999; Mallarino et al., 1998; Lowenberg-DeBoer and Aghib, 1999; Yang et al., 2001) has shown little or no additional yield response with VR P fertilization compared with UR fertilization.

Study of STP changes due to manure application (Table 5) showed that manure always increased STP ($P \leq 0.05$) in the low-testing classes and sometimes in the Optimum class. This result is expected as both application methods applied manure in these areas. Although STP changes in the high-testing areas were rarely statistically significant, there were decreasing STP trends for the control and the VR and increasing trends for the UR in most sampling dates. Again this is expected because the UR applied manure in these areas while the VR and the control did not. The VR method tended to produce a larger STP increase than UR in areas testing Very Low, although this trend was significant only for Site 2 after the second manure application.

Average results of STP change across all fields in Fig. 1 show very clearly that VR increased STP more than UR in low-testing areas and reduced STP in high-testing areas. Analyses of variability for VR and UR methods confirmed that final STP values were less variable for VR than for UR in both sites (the standard deviation of final STP was 4 and 6 mg kg^{-1} for VR and UR in Site 1, and 11 and 17 mg kg^{-1} for VR and UR in Site 2). This was confirmed by a test for equality of variance that showed a significant ($P \leq 0.05$) difference of the variances of the VR and the UR final STP values. This result confirms that VR applied more P to low-testing areas and less P in high-testing areas compared with the UR method. Another important advantage of VR is that it utilized more manure than the UR (5.4 kg P ha^{-1} or 11% on average), and never decreased yield while decreasing STP variability. These results support the possibility of using VR application of liquid swine manure in conjunction with a P index (Mallarino et al., 2001a) to help determine agronomic and environmentally sound manure application to fields.

CONCLUSIONS

The results showed that applying liquid manure with UR or VR methods produced similar soybean and corn yield over two rotation cycles in two fields. Only in one site-year the VR method increased yield further than the UR method in low-testing field areas, but this increase was overshadowed by lack of differences in larger field areas. Over both fields, the VR method applied 11% more manure than the UR method, and reduced STP variability by increasing STP in low-testing areas and decreasing or not affecting STP of high-testing areas. Thus, although use of VR technology may not increase crop yield and economic benefits for producers compared with a UR method, VR allows for better manure management and can reduce the risk of P delivery from manured fields to water resources.

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Table 1. Macronutrients applied with uniform and variable manure treatments to field areas that tested within various soil-test P interpretation classes.

Manure treatment	Soil test class †	Area		Nutrients applied		
		Site 1	Site 2	N	P	K
		------ % -----		---------- $kg\ ha^{-1}$ ---------		
Uniform	All	--	--	168	51	56
Variable	VL	32	27	280	85	94
	L	38	41	224	68	75
	Opt	27	16	140	42	47
	H ‡	3	7	0 (112)	0 (34)	0 (37)
	VH	0	9	0	0	0

† VL = very low, L = low, Opt = optimum, H = high, and VH = very high.

‡ Manure was unintentionally applied to areas testing High the first year at Site 1. Rates for that year are shown in parentheses.

Table 2. Effect of uniform and variable manure treatments on whole-field grain yields.

Field	Year	Crop	Treatment and grain yield			Statistics †
			Check	Uniform	Variable	
			------------- kg ha^{-1} -------------			$P > F$
1a	1997	Soybean	4123	4242	4215	0.20
1c	1999	Soybean	3559	3731	3775	0.01
2a	1998	Soybean	4097	4219	4221	0.21
2c	2000	Soybean	2880	3427	3358	0.01
1d	2000	Corn	8123	9121	9248	0.01
2b	1999	Corn	10057	10683	10589	0.02
2d	2001	Corn	12210	12618	12605	0.01

† Probability of the manure main effect. Comparisons of the uniform-rate and variable-rate manure treatments never were significant ($P \leq 0.05$).

Table 3. Soybean grain yield response to manure for field areas testing within different soil-test P interpretation classes.

Field	Year	STP †	Check	Uniform	Variable	Statistics ‡
			Treatment and grain yield			
			---------- kg ha^{-1} ----------			$P > F$
1a	1997	VL	4104	4092	4270	0.25
		L	4159	4353	4248	0.03
		Opt	4062	4257	4112	0.19
		H	4374	4276	4139	0.37
1c	1999	VL	3430	3715	3759	0.01
		L	3638	3743	3777	0.01
		Opt	3697	3737	3853	0.15
2a	1998	VL	4001	4203	4142	0.02
		L	4080	4258	4214	0.01
		Opt	4090	4220	4166	0.11
		H	4148	4069	4370	0.48
		VH	4430	4203	4480	0.21
2c	2000	VL	2621	3303	3268	0.01
		L	2872	3450	3384	0.01
		Opt	3067	3323	3370	0.16
		H	3173	3568	3297	0.11
		VH	3497	3690	3628	0.27

† STP = soil-test P classes. VL = very low, L = low, Opt = optimum, H = high, and VH = very high.

‡ Probability of the manure main effect. Comparisons of the manure application methods never were significant ($P \leq 0.05$).

Table 4. Corn grain yield response to manure for field areas testing within different soil-test P interpretation classes.

Field	Year	STP †	Treatment and grain yield Check	Uniform	Variable	Statistics ‡
			---------- kg ha^{-1} ----------			$P > F$
1d	2000	VL	7180	8568	9128	0.01 §
		L	8669	9450	9314	0.01
		Opt	9420	9809	9441	0.63
2b	1999	VL	9447	10644	10089	0.01
		L	10204	10831	10865	0.01
		Opt	10012	10594	10396	0.18
		H	10913	10930	10825	0.82
		VH	10664	10099	11007	0.80
2d	2001	VL	11913	12644	12432	0.01
		L	12185	12580	12607	0.01
		Opt	12564	12693	12774	0.03
		H	12612	12590	12690	0.84
		VH	12859	12685	13072	0.94

† STP = soil-test P classes. VL = very low, L = low, Opt = optimum, H = high, and VH = very high.

‡ Probability of the manure main effect.

§ Significant difference between the manure application methods ($P \leq 0.05$).

Table 5. Effect of manure on changing soil-test P for various interpretation classes.

Field	Years	STP †	Treatment and soil-test P change			Statistics ‡
			Check	Uniform	Variable	
			---------------- mg kg^{-1} ------------			$P > F$
1	1997-98	VL	0.3	2.4	3.7	0.01
		L	-0.7	4.3	5.4	0.01
		Opt	-2.7	1.3	0.6	0.01
		H	-4.5	-1.3	-2.5	0.61
1	1999-00	VL	1.2	7.8	9.4	0.01
		L	1.3	6.5	4.8	0.01
		Opt	0.8	4.0	3.4	0.39
2	1998-99	VL	-0.3	4.0	4.3	0.01
		L	-0.2	5.9	5.9	0.01
		Opt	-1.7	3.0	0.1	0.26
		H	-2.2	7.8	1.8	0.02 §
		VH	-3.6	4.0	-2.9	0.57
2	2000-01	VL	2.7	5.4	9.8	0.01 §
		L	1.5	4.1	6.6	0.01 §
		Opt	-2.5	2.5	-6.0	0.94
		H	4.4	2.5	-3.3	0.29
		VH	2.1	5.8	-5.4	0.75

† STP = soil-test P classes. VL = very low, L = low, Opt = optimum, H = high, and VH = very high.

‡ Probability of the manure main effect.

§ Significant difference between the manure application methods ($P \leq 0.05$).

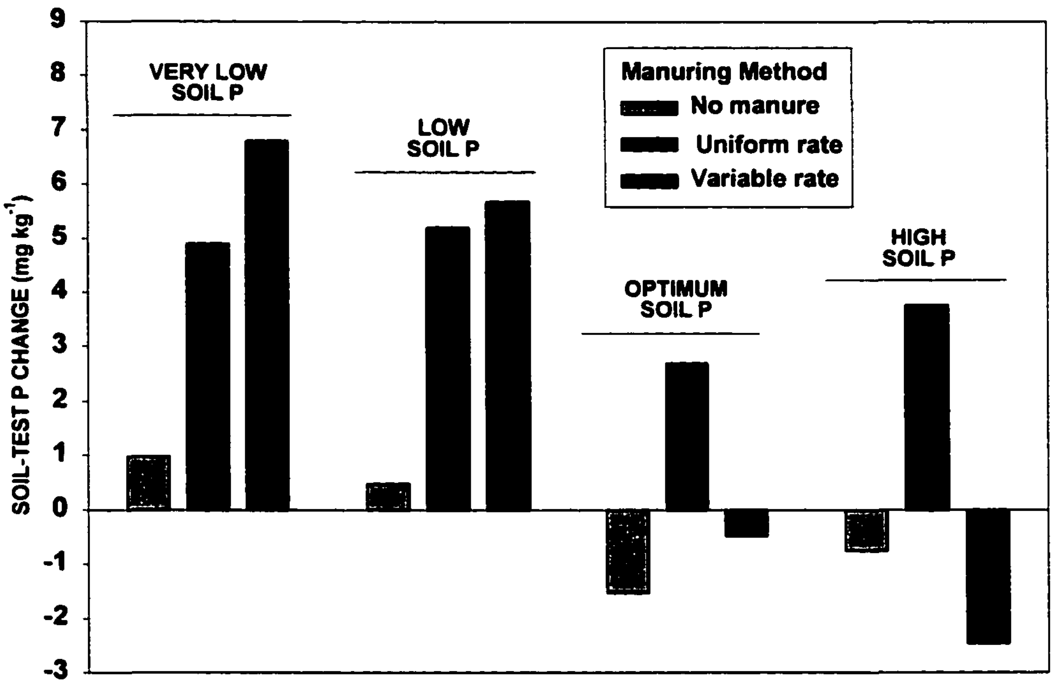

Fig. 1. Effect of the uniform-rate and variable-rate applications of liquid swine manure on soil-test P change after crop harvest for various initial soil-test P interpretation classes (means of 2 years and two fields).

CHAPTER 4.
GENERAL SUMMARY AND CONCLUSIONS

The overall objective of this study was to evaluate crop yield and soil-test P responses to variable-rate application of P fertilizer and P-based liquid swine manure compared with traditional uniform-rate fertilization. Two studies with corn and soybean were used to examine these questions. One study utilized an existing variable-rate P fertilization program offered by an Iowa cooperative, while the second study utilized liquid swine manure as the P source and farmers' equipment. The methodology included various farmers' fields and on-farm, strip-trial research methods that were adapted to precision farming tools such as intensive grid soil sampling, combines equipped with grain yield monitors, differential global positioning systems, and geographical information systems. This methodology allowed for the splitting of grain yield and soil-test data from large areas into smaller areas to study crop and soil responses for different parts of fields.

Phosphorus fertilization and P-based application of liquid swine manure often increased whole-field crop grain yield in fields in which both mean and median soil-test P were within or below the lower part of the Optimum interpretation class for corn and soybean production. Analyses of yield for field areas with contrasting soil-test P values often showed significant responses to fertilizer or manure P in field areas testing Optimum or less, but rarely in high-testing areas. Phosphorus fertilization increased early plant growth (V5 to V6 growth stage) and early P uptake more frequently than grain yield (these measurements were not collected for the manure study), and responses sometimes were observed in high-testing field areas.

The method of P application (variable or uniform) did not influence whole-field or within-field grain yield, early growth, or P uptake. However, the variable-rate method reduced the amount of P fertilizer applied compared with the uniform application method but increased the amount of manure P applied. This contrasting result for the fertilized and manured fields was related to different soil-test P values and variability (i.e., different distribution across interpretation classes) for the fields and not to the P source. For example, similar differences in amounts of P applied would have been observed if P fertilizer had been applied to the manured fields.

The lack of difference between fertilizer or manure application methods could be explained by several reasons. One reason is that P rates applied to low-testing areas with both methods were sufficient to produce maximum crop yield. The P fertilizer recommendations used in Iowa and the Corn Belt for low-testing soils either include an explicit build-up component or recognize that the amounts recommended for low-testing soils will result in soil-test P build-up over time. Moreover, the one-time application of the 2-year P recommendation for the corn-soybean rotation used in this research should have resulted in sufficient P to maximize yield of the first crop of the rotation with both application methods. The other reason relates to very high small-scale soil-test P variability or inadequacy of the soil sampling methods used. Although the grid-point sampling method used is the most frequently used method in Iowa and the Corn Belt, soil-test P data for at least some fields suggest that this method did not describe soil-test P variability appropriately. Results of complementary research indicate that a grid-point sampling method based on grid distances even smaller than those used in this study may not provide reliable information, and that alternative soil sampling methods need to be developed to achieve the maximum potential of variable-rate fertilization.

Although yield responses to P fertilizer or manure P did not differ, the variable-rate method reduced soil P variability compared with the uniform-rate method by increasing soil-test P in low-testing areas and decreasing or not affecting soil-test P of high-testing areas. This difference was more pronounced when the system was used through more than one rotation cycle as was the case in the manure study. Thus, even if the use of the variable-rate application method does not increase crop yield compared with a uniform-rate method, its use allows for better distribution of fertilizer or manure.

Overall, this research showed that precision farming technologies are useful tools for improving nutrient management. Furthermore, the research demonstrated that a combination of traditional on-farm strip trials and precision farming technologies can be used to evaluate management practices and their interaction with soil properties within farmers' fields. The results suggested that fertilization or manure application programs that vary the nutrient application rate may not result in large economic benefits because yield was not increased compared with the less expensive uniform-rate application method. However, use of variable-rate technology will result in better nutrient management and perhaps better water quality because of more efficient distribution of fertilizer or manure. In order to achieve these benefits, nutrient application should be based on cost-effective and reliable estimates of nutrient availability.